29. Mitteldeutsches Bau-Reko-Kolloquium
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Historical structures for modern times, secured by respectful engineering support

(Historische Tragwerke in der neuen Zeit, gesichert durch respectvolle ingenieurmäßige Begleitung)

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Abstract

The structural integrity and load distribution schemes in historical buildings are mostly based on the experience of the original building master, and much less or not at all on building mechanical analysis. The combination of historical experience with today's analytical understanding of force distribution in structures enables solutions to adapt historical constructions to actual codes and standards. Examples of restoration and revitalization of masonry, concrete and timber structures are given to clarify such procedure.

Zusammenfassung

Die Tragwirkung historischer Gebäuden ist meistens basiert auf Baumeisterlicher Erfahrung, und weniger auf Baumechanischer Analyse. Die Kombination von historischer Erfahrung mit dem heutigen analytischen Verstehen von Last- und Kräfteverteilung in Tragwerken, ermöglicht Lösungen um historische Bauten auf respektvoller Weise an die modernen Regeln und Normen der Tragfähigkeit an zu passen. Mit Beispielen von Holz-, Mauerwerks- und Stahlbetonkonstruktionen aus der Frühzeit des Stahlbetons wird diese Vorgehensweise erleuchtet.

Keywords: restoration, historical structures, masonry, concrete, timber, structural analysis

1. Introduction

In dealing with the preservation process of historical buildings different steps have to be envisaged, according to the basic steps proposed by the International Council on Monuments and Sites ICOMOS [1]:

- *Anamnesis.* Significant and objective information of the building and of its history is collected. Data are gathered from literature, direct visual observation and field research.
- *Diagnosis.* The causes of the damage and decay are determined. Also the safety level is evaluated. Eventually a monitoring system is installed to support the diagnosis and therapy processes. Not only deterministic but also newly developed probabilistic procedures are used to evaluate the load-bearing capacity of the structure.
- *Therapy.* If necessary, one or more therapies are proposed to repair and upgrade the building. The therapies should be accompanied by a prognosis of the expected lifetime after restoration, and the necessary maintenance interventions and frequency.
- *Control.* Checks are carried out during and after intervention, eventually using the previously installed or a newly installed monitoring system.

Especially actual load bearing demands may put extreme requirements to the existing historical structure. Development and use of structural consolidation and strengthening techniques must be based on the true nature and stress-strain behaviour of the used building material concrete, masonry or timber, as well as on the understanding of the load distribution and deformation mechanisms acting in such structures. Safety, reliability and risk are key issues in rehabilitation as well as in the preservation of the built, cultural environment.

Powerful methods are becoming available for the calculation of structural safety values. They allow the calculation of the global probability of failure of complex structures. These methods need appropriate analysis models as input, as well as reliable design models for strengthening of structural elements by means of externally bonded steel plates or fibre reinforced laminates, design models for the effect of grouting on strength and stiffness of ancient brick or block masonry and/or models for the design of timber strengthening. Such models are derived from research, which combines investigation and development of new materials, non-destructive testing, laboratory and on site investigation. This global approach, in which theory and practice are combined, is the ultimate goal of every restoration or rehabilitation process according to WTA-concepts [2]. The case studies below show how Triconsult nv, a K.U.Leuven spin-off design office for restoration and revitalisation, tries to implement the above principles in restoration design practice.

2. Reinforced Concrete: Steam Mill at Overijse, Belgium

The building “Vuurmolen (Steam Mill)” at Overijse is one of the earliest concrete buildings in Belgium, constructed in 1902, Figure 1. It is an example of the complexity in gathering data for the compressive strength of the building material at hand – concrete – from an historical building.

Figure 1 Steam Mill at Overijse (constructed 1902)
Dampfmühle in Overijse (Baujahr 1902)

During the assessment, the strength of the reinforced concrete beams and columns has been determined. Because the building is listed, the number of destructive tests had to be minimized. The concrete compressive strength is determined using a combination of both destructive (DT) and non-destructive (NDT) tests: compressive tests on drilled cores (DT), ultrasonic testing (NDT) and sclerometer (rebound hammer) testing (NDT).

The sclerometer values are transformed into values of the compressive strength using the calibrated curves of the rebound hammer. The ultrasonic measurements are transformed into compressive strength values using:

$$E = \frac{\rho(1+\nu)(1-2\nu)}{(1-\nu)} c^2 \tag{1}$$

where: E is the modulus of elasticity, ρ = 2400 kg/m³ the concrete density, ν = 0.2 Poisson's ratio and c the measured velocity based on the measured thickness and travelling time of the ultrasonic wave propagation through the material.

The compressive strength results from (Eurocode EC 2, ENV 1992-1-1:1999):

$$f_{ck} = \left(\frac{E}{9.5}\right)^3 - 8 \qquad (E \text{ in kN/m}^2) \tag{2}$$

The European probabilistic design code proposes a lognormal probability distribution function (PDF) to be used for the concrete compressive strength material model. As the compressive strength can only have non-negative values and because the relatively heavy tail for higher values of the compressive strength, a lognormal distribution is more appropriate than a normal (Gauss) distribution. A histogram of strength results, as well as fitted normal and lognormal distributions are plotted in Figure 2.

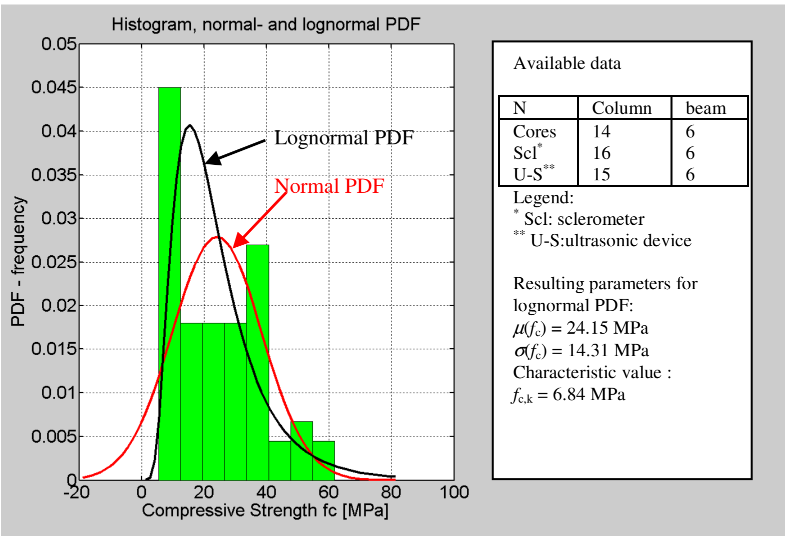

Figure 2 Experimentally determined compressive strength – Vuurmolen Overijse
Gemessene Drückfestigkeiten – Dampfmühle Overijse

Using a normal or lognormal distribution for the material property might have significant consequences on the failure probability. As an example, both probability distribution functions are used on the R-S problem (R = strength; S = load level) of a concrete column in the building. This leads to the following results for the reliability index β:

- β = 1.67 or P_f = 0.047 in case of a normal probability distribution function,
- β = 5.79 or P_f = 3.52 10^{-9} in case of a lognormal probability distribution function.

This corresponds to a characteristic compressive strength value of –3.9 MPa for a normal (Gauss) distribution, opposite to +6.8 MPa for a lognormal distribution. The first value initially led to the pulling down option, whereas the second approach was the basis for the life-saving and renovation of the building.

Remark that in the first case, the structure is far from the preset target reliability, preset in Eurocode EC 0 (EN 1990-1-1:2002), $\beta_T = 3.8$. In the second case, the structure is judged to have a sufficient reliability. Based on these positive results, the structure has been restored and saved, Figure 3 [3].

Figure 3 Ground level, CFRP wrapping of columns and shear strengthening of beams
Erdgeschoß, CFRP Umwicklung von Stützen und Querverstärkung von Balken

3. Soil-Structure interaction: Church of Saint-James, Leuven, Belgium [4]

The construction of the western tower of the church of Saint-James dates back from 1220. During several subsequent building phases, the Romanesque church has been replaced and enlarged by a church nave and transept in early Gothic style, Figure 4, and an 18th century neo-classicistic choir.

The structure itself is located on an earlier swamp, reclaimed by the monks at the time of construction. The load-bearing capacity of the subsoil is limited, causing large differential settlements. At several occasions in the past, restoration works took place. Due to the excessive cracks observed however, it was decided in 1963 to close the church envisaging its structural collapse, to remove the severely cracked masonry vaults of the side naves and to shore up the pillars of the main nave.

These measures were dictated by the feeling that the tower was leaning against the nave, and was pushing the nave-walls towards the transept, Figure 5.

Of course, the nave and transept columns were not stiff enough to resist such pushing forces, and therefore the transept opening was stiffened with heavy concrete columns supported by steel trusses, Figure 6.

Moreover, the nave columns were unloaded by supporting the nave walls with heavy steel beams positioned on steel trusses, Figure 7.

It is clear that since 1963 and up to now the church has been out of use. Fortunately, the project ran out of funding, and contractor works were stopped in 1971. Since then, monitoring was made with irregular intervals, and finally a profound study of the church deformations was executed by Triconsult nv in 2007 [5]. This study revealed that the crack patterns and deformations did not at all correspond to the assumed deformation scheme given in Figure 5.

Figure 4 Saint-James' church: Romanesque western tower; Gothic nave and transept
Sankt Jakobskirche: Römischer Westturm; Gotisches Schiff und Querschiff

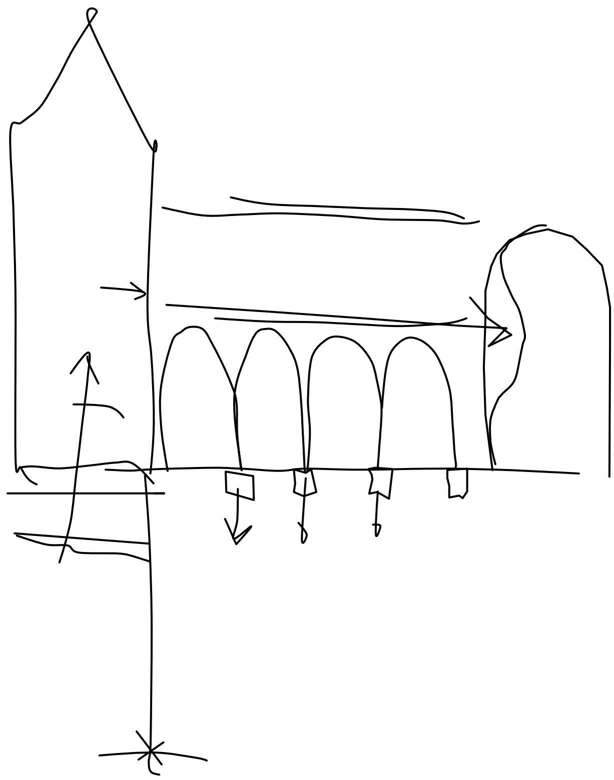

Figure 5 Leaning tower and presumed deformation scheme (architects drawing discovered at rood loft in church)
Überhängender Turm und vorausgesetzte Verformungen (Zeichnung des Architect, entdeckt im Doxale)

Figure 6 Stiffening concrete column and steel trusses against crossing columns in transept
Versteifende Betonstützen und Stahlgerüste gegen den Vierungstützen im Querschiff

Figure 7 Supporting structure for the nave walls
Tragende Hilfskonstruktion für die Schiffmauer

The nave columns undergo larger settlements than the tower and the transept, and the nave walls are loaded as beams, deflecting in between the tower and the transept, Figure 8.

The tower is not leaning and pushing against the nave. Therefore, the concrete stiffening columns and the stiffening trusses are not needed. The preliminary works, executed in the period 1963-1971, are now a major part of the restoration problem or project. The therapy will essentially consist of the following different phases and measures: strengthening of foundations of columns and tower; consolidation of nave columns; crack repairs; removal of concrete and steel stiffening elements.

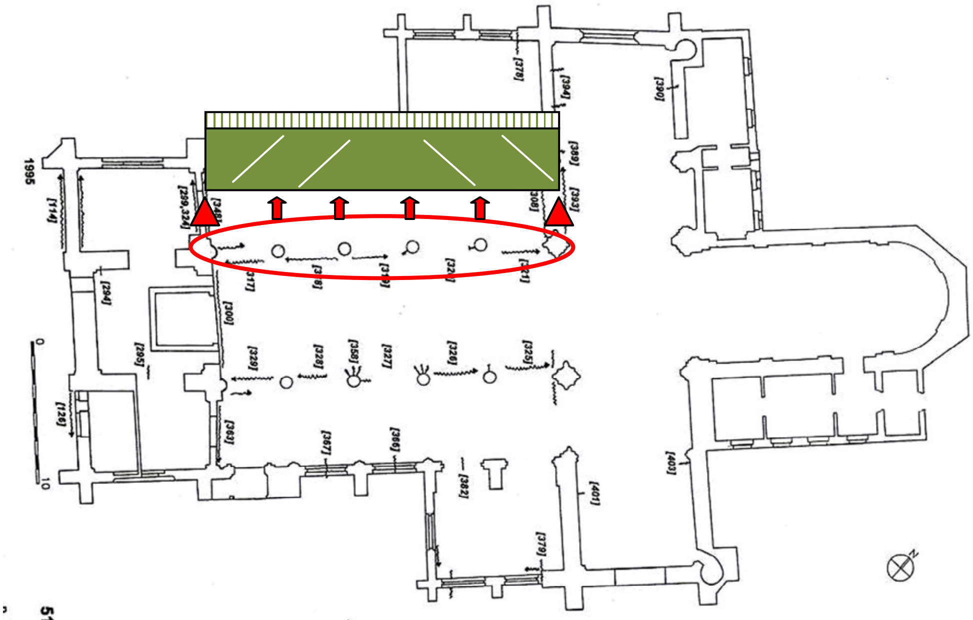

Figure 8 Plan of church, with scheme of cracks in nave walls
Grundriß der Kirche, mit Rißbild in der Schiffmauer

4. Archaeological cellar under Our Ladies Basilica at Tongeren, Belgium

4.1. Project description

Tongeren is an old Roman city, with a history of more than 2000 years. The city centre is an accumulation of remains of successive civilisations and cultures. Archaeological research at the south side of the church revealed the remains of two different defensive walls of the medieval Minster, one dating from the 10th century and one from the 12th century. At the same time, a Roman town house with bathhouse from the 2nd and 3rd century was discovered, as well as a tower and connecting sections of the 4th century town wall. The archaeologists were convinced that the remains of the bathhouse were only the southern exterior walls of a rich urban residence, of which the remaining parts are situated under the Basilica, Figure 9.

The idea grew to disclose the remains under the church. However, religious life in the church is very active, and the church is an important monument as well. One had to look for a solution that could combine the desires and needs of all parties involved. The proposed solution was the construction of an archaeological cellar under the church, as an underground archaeological field. The cellar will have no solid concrete bottom floor. Visitors will walk on bottom soil surface of the excavations, to keep the archaeological sensation as complete and as realistic as possible. From the beginning on it was clear that the excavation of an archaeological cellar underneath the existing church structure would cause great structural problems.

Figure 9 South view of Basilica at Tongeren
Südsicht auf die Basilika von Tongeren

From existing small cellars it was estimated that foundation depth of walls and columns would be about 2.7 to 3.0 m. The necessary excavation depth for an accessible cellar, taking into account the necessary space for a roof plate and new flooring system for the church, would be 3 m. To give the visitors the real feeling of an archaeological site, and not of a crypt under the church, it was decided to excavate the central nave and the adjacent aisles as well as part of the choir. This presents a surface of about 20×40 m², in which the column footings and the wall foundations would be stand-alone elements. Removing of the soil around the foundations also takes away the constraining action of the soil on the foundation masonry. Moreover, the direct foundations at depths of about 3 m than become direct foundations on the soil surface.

The load carrying capacity of surface foundations is very limited and uncertain, and would certainly lead to excessive differential settlements. Moreover, the unconstrained rubble masonry of foundations has nearly no strength. Both effects significantly endanger the structure, leading to an almost certain collapse. Therefore the project was preceded by a preliminary investigation to reveal the composition and quality of the foundation masonry, and to study possible injection grouts for consolidation of the masonry, to strengthen it sufficiently to be able to transfer the anchoring forces of the micro piles, Figure 10. The underpinning of all the columns and walls in and adjacent to the excavation will avoid such differential settlements. The micro piles must be anchored in a stable masonry, able to take up the concentrated forces of 200 kN each from these piles [6]. Therefore the masonry walls were injected with mineral grout.

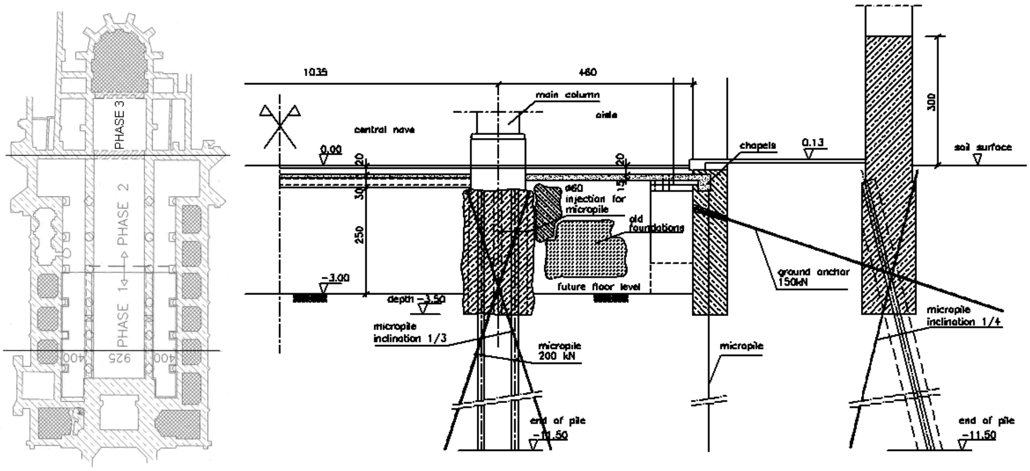

Figure 10 Left: Plan of the church with excavation phases I and II. Right: Cross-section of the archaeological cellar.
Links: Grundriß der Kirche mit Ausgrabungsphasen I und II. Rechts: Durchschnitt des archäologischen Kellers

The whole project was divided in several phases. Phase I is the excavation and re-arrangement of the west part of the church (1999-2001); phase II concerns the central part of the church (2004-2006); phase III concerned the choir (2006-2008). Excavation works and consolidation and strengthening as well as re-arrangement works were going on simultaneously. This meant a lot of organisation and compromise between archaeologists, contractor, designers and users. The consolidation procedure was adapted according to the findings in the preliminary investigations.

4.2. Development of consolidation grout

4.2.1. Compositions

In phase I, a pure cement grout was used for the consolidation of the foundation masonry. This grout had been developed for the consolidation of the tower masonry in 1993 [7]. The "injectability" of a cement grout depends, among others, on the fineness of the dispersion of the cement particles in the water phase. The addition of superplasticizers and stabilizers prevents the dispersion from coagulation and segregation. The injected cement-based grout was a mixture of cement, admixtures and water (see also Table 1, composition 1).

Table 1 Compositions of the binary grouts for the injections during phase II.

Component:	CEM III/A 42.5 N LA	Bentonite	$Ca(OH)_2$	Water	Glenium 27	W/B ratio
	[kg]	[kg]	[kg]	[kg]	[kg]	[-]
Composition 1	100	2	-	67.5	1	0.675
Composition 2	50	-	50	67.5	1	0.675
Composition 3	60	-	40	67.5	1	0.675
Composition 4	70	-	30	67.5	1	0.675
Composition 5	80	-	20	67.5	1	0.675

Remark: Composition 1 is used as a reference, it is the cement-based grout used in phase I.

Although the main objective concerning the consolidation and strengthening of the foundation masonry was successfully executed with the cement based grout in phase I of the project, there were some disadvantages using this type of grout. Cement based grouts tend to remain very fluid for several hours, causing damage. Some valuable inscriptions on lime stone fragments were lost and even a skeleton was accidentally injected, Figure 11(b).

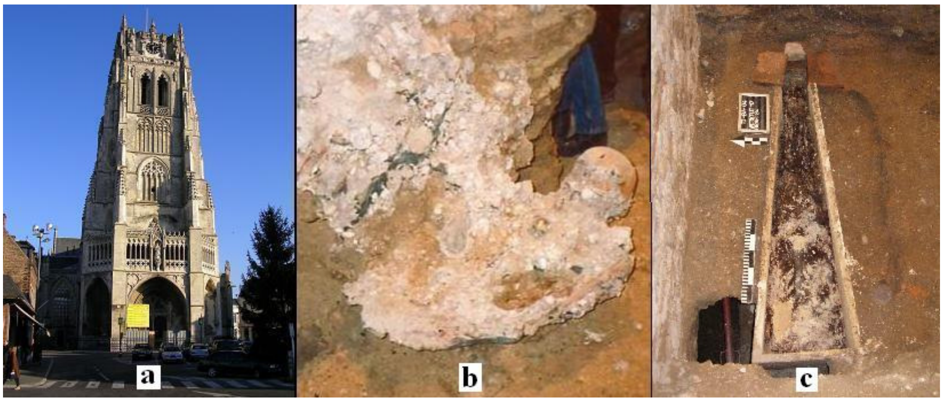

Figure 11 (a) West view of the tower of the Basilica at Tongeren; (b) Unwanted "consolidation" of a skeleton; (c) Sarcophagus next to the chain wall (excavated in phase II)
(a) Westsicht auf den Turm der Basilika von Tongeren; (b) Unerwünschte "Konsolidation" von ein Skelett; (c) Sarkophag annähernd der Kettenmauer (ausgegraben in Phase II)

In phase II, it was attempted to prevent this unwanted filling of sarcophaguses, skeletons and inscriptions by using a different grouting material. The aim was to develop a mixture that not only satisfied all the requirements needed for structural strength but also limited the fluidity in time. In that way, the unwanted consolidation of valuable artefacts is reduced to a minimum.

It is known that the mechanical properties of the grout hardly influence the final compressive strength of injected masonry in case of comparable injectability. Adhesion of grout to stone and mortar is more important. Therefore, it is preferable to focus on rheological properties of the grout and on tensile or adhesion strengths instead of on compressive strength. A second category of requirements could be named "compatibility" with the original material. The grout needs to be adapted to the original material with regard to three aspects: chemical (including durability), mechanical/structural and physical compatibility. Special attention is paid to the aspect of historical compatibility keeping in mind the original composition of the mortars.

In order to fulfill the requirements, it was decided to examine several mixtures of binary grout using cement and air hardening lime as basic materials. Table 1 shows the different mixtures that were tested. Table 1 mentions the W/B (water/binder ratio by mass) in stead of the W/C ratio because the binder is a mixture of cement and air hardening lime. This W/B and the amount of superplasticizer (Glenium 27, based on chains of polycarboxylate ether) were kept constant. Practical experience showed that higher amounts of superplasticizer increased shrinkage; lower amounts require too much water. The following mixing procedure was used: dry mixing of cement and calcium hydroxide, addition of 90% of the water and 2 minutes mixing (2400 r/min), after 2 minutes rest, addition of 5% water with 50% of superplasticizer amount and mixing for 3 minutes (2400 r/min), after 2 minutes rest, addition of the final amount of water (5%) with the last 50% of superplasticizer and mixing for 2 minutes (2400 r/min).

A two years test programme was implemented to study the long-term effects of the grout mixtures of Table 1. The tests were done on samples 40×40×160 mm³ according to the European standard NBN EN 1015-11:1999 for compression and flexural strength. The environmental conditions of the samples were kept constant for the first 90 days at relative humidity (R.H.) > 96%; CO_2-content 3% (using a CO_2-incubator) and temperature of 20°C.

Then the samples were divided into two groups A and B, corresponding to a relative humidity > 96 % (group A) and equal to 85 % (Group B) for a two years testing period. The idea is to study the long-term effect of delayed carbonation of the air hardening lime on the cement-matrix (instantly formed during the hydraulic reaction). Therefore a CO_2-amount of 3% is used (normally the CO_2-content in the atmosphere is 0.03-0.04%) to accelerate the carbonation process. By keeping the R.H. high (> 96%) for the first 90 days, the hydraulic reaction of cement will dominate the curing process. By reducing the R.H. to 85% after 90 days (group B), the carbonation process will take part in the curing process and the long-term effects on the mechanical properties can be studied.

4.2.2. Physical and mechanical properties

The stability is checked by measuring the bleeding which can be read from the scale on a lab tube in which the grout is poured. The bleeding was measured after 0', 15', 30', 60', 90' and 120'. It is concluded that the higher the content of cement, the higher the bleeding will be. Air hardening lime acts as a very good stabilizer. Composition 1 produces the most bleeding, but still keeps bleeding under 3%, which is regarded to be tolerable for grout mixtures.

The fluidity test is performed with a Marsh funnel Viscometer according to the American standard ASTM C 939:1987. The Marsh cone used was an OFITE and is calibrated so that it takes 26 ± 0.5 s for 947 ml of water (21 ± 3°C) to pass the funnel. Figure 12 gives the Marsh cone flow times of the different compositions tested for phase II. The flow times were measured after 0', 15', 30', 60', 90' and 120'. It was the aim to develop a grout which fluidity stays constant during the first one and a half hour and then decreases rapidly. Figure 12 clearly shows that compositions with an air hardening lime content above 30% fulfill this special condition needed to prevent the filling of the valuable artefacts.

The injection test consisted of the injection with grout (composition 3), under a constant pressure of 1 bar, of a plexiglass column, which was filled with gravel (broken bricks). The crushed bricks show a water absorbing action comparable to the real situation. The size of the brick particles varies between 1 mm and 2 mm. The grout proved capable of consolidating the gravel.

The compressive and flexural strength tests were executed after 28, 90, 180, 365 d. Figure 12 gives the evolution of the compressive and flexural strengths of the different compositions of both groups. Higher cement content results in higher compressive strengths. The compressive strength of group B tends to decrease slightly after a year. The flexural strength depends on the amount of cement and the relative humidity. Group A (R.H. > 96%) shows no decrease of the flexural strength after 365 days. For group B, a cement content of 70% is observed to be a minimum to prevent dropping of the flexural strength. The drop of flexural strength is probably due to microcracking occurring at the interior of the samples. It is assumed that the reason of this microcracking is caused by drying or by the difference between areas of the grout situated towards the exterior of the specimen that are carbonated and other areas towards the interior, that are still hardening. Hydration causes chemical shrinkage and induces tensile stresses (and thus microcracking) at the interface of a carbonated (and thus inert) part of the material and a non carbonated (and thus hydrating) part of it. After considering all the objectives, it was decided that composition 4 (70% cement, 30% slaked lime) corresponded best with all the requirements stated above and therefore was used on site.

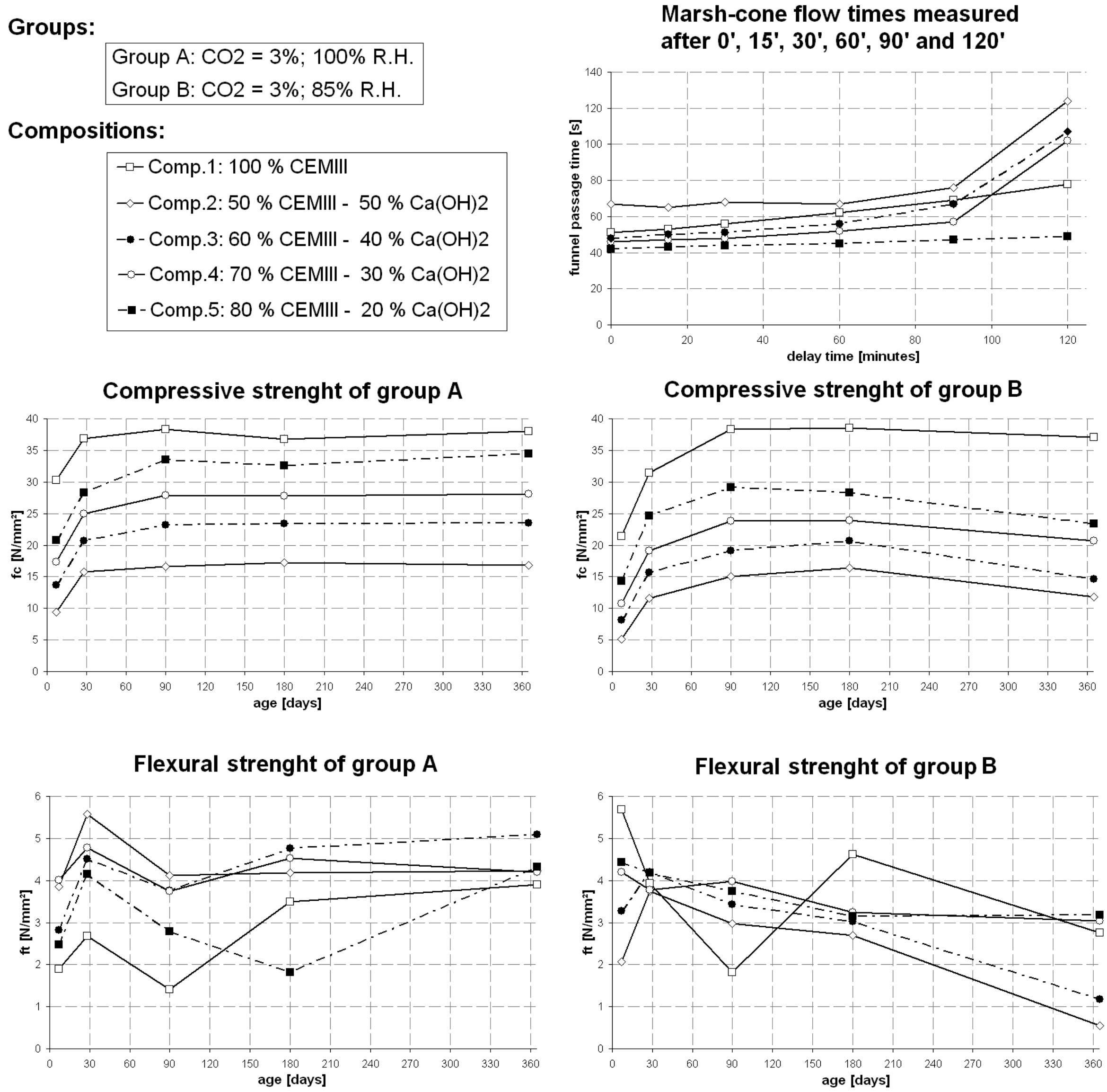

Figure 12 Marsh-cone flow times and compressive and flexural strength of the different compositions
Marsh-Becher Fließzeiten und Druck- und Biegezugfestigkeiten der Mischungen

Figure 13 gives an impression of the church nave during the excavations.
Figure 14 gives an impression of the finished archaeological cellar, walking between foundations of Romanesque (left) and Gothic foundations.

Figure 13 General view of the excavations. Steel struts prevent buckling of wall-column system
Übersicht der Ausgrabung im Schiff. Stahlstützen sichern gegen ausknicken des Mauer-Säule Systems

Figure 14 Archaeological cellar, situation March 2007
Archäologischer Keller, Stand März 2007

5. Monument-Society interaction: Revitalization of burnt-down Abbey Tower at Sint-Truiden, Belgium

5.1. Problem formulation

The idea of restoration of monumental constructions and buildings goes back to the 19th century. Conservation as an essential aspect in monument care is a concept from the 20th century. The vision and attitude towards restoration and conservation depend on place and time. This vision is determined in a number of Charters, of which the most well known is the Venice Charter of 1964. These charters are important directives for actual restoration and conservation practice. Restoration in many cases means an additional cost compared to new construction with equal functionality. This extra cost must be justified by the conservation of authenticity and by the potential contribution to sustainable development. The restored

building must be integrated in the built and in the social environment: it must contribute to sustainable development in material as well as in social sense.
The restoration of the tower of the Saint-Trudo Abbey at Sint-Truiden is an example of such a tedious, balancing and mostly time consuming process [8]. The tower is the only remaining part of the medieval church (1055-1082) constructed by abbot Adelardus II. Before 1975, the central market place of Sint-Truiden was dominated by three towers: the tower of the Abbey, the tower of the City Hall, and the tower of the church of Our Lady Mary, Figure 15.

Figure 15 Market place of Sint-Truiden before 1975, view to east: left Abbey Tower; middle City Hall Tower; right Our Ladies Church Tower (1926) (Fototheek Sint-Truiden)
Marktplatz von Sint-Truiden vor 1975, Sicht nach Osten: links Abteiturm, zentral Rathausturm und rechts Liebfrauenkirche (1926) (Fototheek Sint-Truiden)

Figure 16 Fire of 09.12.1975, attacking tower, church and school buildings in former abbey (Fototheek Sint-Truiden)
Brand von 09.12.1975 zerstörte Turm, Kirche und Schule der Abtei (Fototheek Sint-Truiden)

On 9th December 1975 the abbey church completely burned down, Figure 16, and the tower was transformed into a ruin. After long and tedious discussions of the Flemish Heritage and Monuments Department with owners and the population of the city of Sint-Truiden, it was finally decided to open up the ruin of the tower by making it accessible to people, as part of the rehabilitation project "Kerkveld" (Church Field) comprising not only the tower, but also the remains of the former church, its crypt, a small theatre, all connected to the Great Market place of Sint-Truiden. The architect in charge was Team Herman van Meer. The project was executed in 2003-2004. It took more than 25 years before a final decision was taken on what the goals of the restoration project should be. Immediately after the fire, the population wanted a reconstruction of the church. Soon after, the demand decreased to a reconstruction of the classicistic spire with gallery, dating from 1779. The discussion kept dragging, and a sponsor proposed a temporary metal ‘millennium spire’ to be installed for the 2000 millennium celebrations, Figure 17.

Figure 17 Ruin of tower after fire of 1975, with millennium spire (2000)
Turmruine nach dem Brand, mit Millennium Spitze (2000)

Indeed, the metal spire was installed for the millennium turn 2000, with webcams that could be consulted via internet. However, this construction could not please the inhabitants of Sint-Truiden. So discussion on the restoration started again, leading to the project of integration and opening up of the tower, as it was executed in 2003-2004 [10].

5.2. Opening up of Abbey-Tower

The visitor enters the church field through the Baroque gate, Figure 17. He enters the tower through the old passage from church to tower, Figure 18.

A steel staircase at the inside of the shaft leads the visitor to the “Emperor’s loge”, where the emperor used to sit when attending the holy Mass.

Now the visitor stays in the church space. From below one could get a global picture of the east façade of the tower. Now the visitor can nearly touch the wall, and read the traces of construction history. A stairway leads from the emperor’s loge to an opening up platform at the level of the Baroque gate, Figure 19.

Figure 18 Entrance of tower through passage door at ground level. View from entrance to crypt. Stainless steel columns simulating church columns.
Turmeingang im Erdgeschoß. Sicht aus dem Kryptaeingang. Edelstahlphäle simulieren die Kirchensäulen.

Figure 19 Observation platform at level of Baroque gate
Aussichtsplattform über das Barocktor

From this platform, the link between abbey and town can be discovered, as well as the urban elements connected with it. The top part of the gate wall serves as parapet, so that direct contact and touching of the walls is possible.

A veiled but still transparent staircase leads higher to the top of the old Ottonic church tower. At the level of the belfry windows of this Ottonic tower the visitor enters again the tower through a small opening. Via the old spiral stair in the north staircase tower the visitor climbs to an internal platform at the level of the actual belfry windows. Through these windows the contact with the site as a whole is restored.

From this internal platform a steel staircase leads to the panoramic platform on top of the tower. This platform is slightly separated from the mass of the tower shaft, Figure 20.

Figure 20 Panoramic platform and descending spiral stair
Panoramische Plattform mit zurückgehender Spiraltreppe

The top platform allows a walk-round, and symbolises the panoramic view. The opening in the middle connects the inner with the outer space of the tower. The descending steel spiral stair continues in the south spiral staircase tower, and leads the visitor back to the church field.

6. Timber structures: Abbey barn at Herkenrode, Hasselt, Belgium

6.1. Introduction

The Abbey at Herkenrode was founded in 1182. From 1271 till the end of the Ancien Régime, Cistercian nuns controlled the abbey. In that period the abbey was one of the most prominent convent communities in the Low Countries. After the religious wars in the 17th century, a new large construction campaign took place at the abbey site. The abbey had to be self-supporting. Therefore a barn and a water mill were constructed. Fulfilling religious and social tasks, the nuns got paid one tenth of the crops of the surrounding farmers. This payment was stacked in the barn.

At the end of the 18th century, the French confiscated the abbey and sold the buildings and its surrounding territory. Due to a lack of maintenance, the buildings deteriorated rapidly in the 19th and 20th century.

In 1998 the Flemish Community bought a large part of the territory and the buildings. The Foundation for Flemish Heritage received a permanent building lease for the buildings and the surrounding territory. In August 1998, architect Herman Van Meer and his team were appointed to develop a complete restoration plan of the abbey site, including the barn. Triconsult nv is responsible for the structural aspects of the project [11]. An urgent restoration of the barn was needed. Therefore a structural restoration was planned, conserving a maximum of original material of the barn. The barn is shown in Figure 21.

Figure 21 Abbey Barn before restoration
Zehntscheune vor Restaurierung

6.2. Structural problems

Due to a lack of maintenance, the wooden roof structure was heavily deteriorated. Large roof parts had disappeared, causing wood deterioration due to water infiltration. The entire wooden structure was in bad condition. The high moisture content of the wooden structure was an ideal climate for fungal growth.

The large structure (length: 50 m, span: 19 m and height: 15 m) suffered from large lateral wind actions. A lot of joints were inadequate to take the induced forces. Also the masonry walls seemed to be bulged due to the wind load on the roof structure in the past. This was counteracted by the construction of a diaphragm wall and buttresses, as shown in Figure 22.

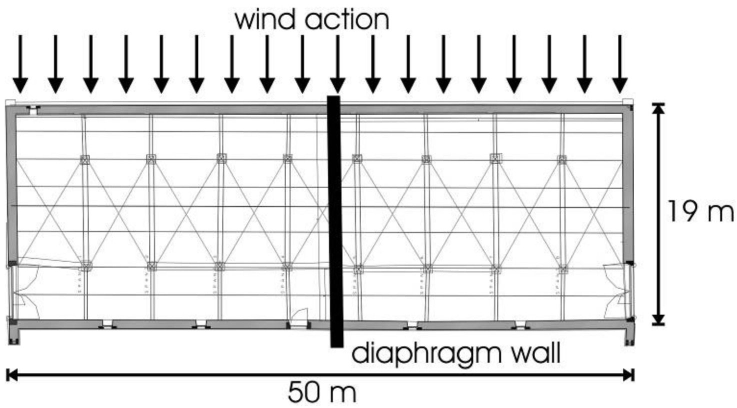

Figure 22 Diaphragm wall
Diaphragma Mauer

However, an insufficient foundation of the oak wooden columns and the large weight of the products stored in the barn caused an important settlement of these columns. The vertical movement of the columns imposed a horizontal pressure on the masonry walls. A scheme of these deformations is shown in Figure 23. Witnesses of these movements are the opened connections between the columns and the horizontal beams connected to the walls.

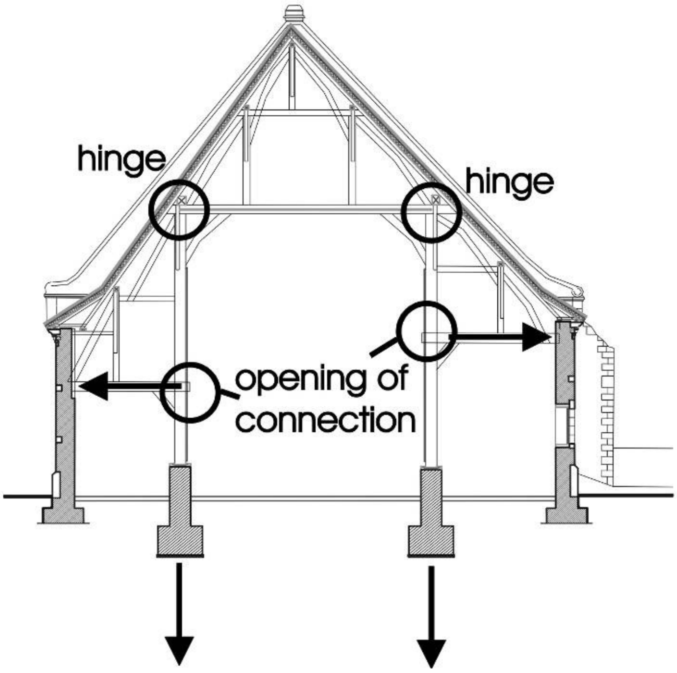

Figure 23 Differential settlements caused horizontal loads on the walls
Differentielle Senkungen verursachten horizontale Kräfte auf die Mauer

6.3. Structural solutions

The wooden structure of the barn was in a bad condition and the repair of the roof and the rafters is a major part in the restoration costs. The replacement of deteriorated wooden parts by new parts was limited as much as possible. Instead, polymer mortar to replace or reconnect broken parts is used. Epoxy mortar is an excellent material to be used for the repair of wood, because it has a strong bond to wood, and its modulus of elasticity is nearly equal to that of wood. The ductile behaviour after first cracking is assured by the glued in anchoring rods. Additionally, epoxy is not affected by moisture.

The repair of deteriorated beams is executed in different steps. After the removal of the bad parts, stainless steel rods are put in place to ensure a good connection between the sound wood and the polymer mortar. In most cases the sound part of the beams or columns can be used as a formwork. If not, a small piece of new wood is used as formwork. After that, the polymer mortar is poured into the cavity. After 7 days the mortar has reached its full strength and the structural integrity of the beam is restored.

The design and calculation method for these strengthening techniques is based on an experimental program, executed at the Reyntjens Laboratory of the K.U.Leuven, as described in [12].

To prevent further settlements of the oak wooden columns, a new concrete foundation was designed, Figure 24. This foundation has a larger contact surface and is constructed at a larger depth where good soil conditions were at hand. The connection between the wooden column and the concrete pedestal has to work as a hinge. This is obtained by drilling in 4 steel anchors, which cross each other in the interface between the pedestal and the column.

The major challenge was to improve the wind stability of the large structure. The diaphragm wall was not original and should be removed to enable a multi-purpose use of the barn. Computer simulations of wind actions on the barn structure showed that the stiffness of the wooden structure was too low. Wind loads could cause deformations in the wooden structure up to 10 cm, thus inducing unacceptable forces on the masonry walls. To decrease deformation of the structure due to wind action, a number of measures were taken.

First the wooden columns were stiffened by means of steel plates. These plates were bonded to the columns with an epoxy-resin. The reinforcement of wooden beams with externally bonded steel plates is a technique adapted from the concrete reinforcement technology. By bonding a steel plate to the wooden column the total stiffness of the column is increased, which decreases possible deformation of the structure.

The stiffened column is shown in Figure 24.

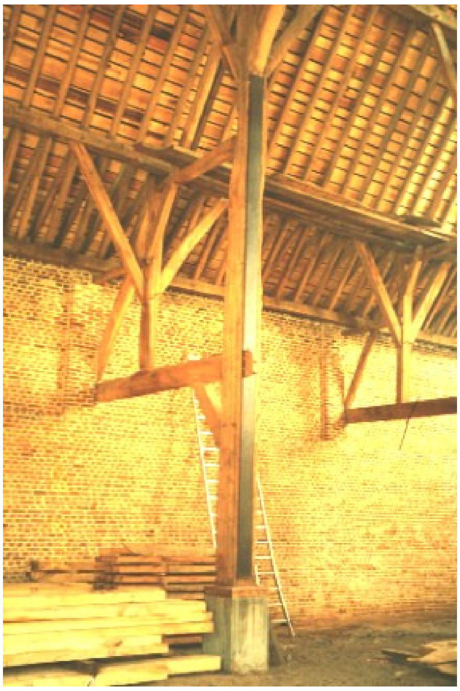

Figure 24 Bonded steel plate on wooden column, supported by new concrete pedestal
Geklebte Stahlplatte auf Holzstütze, ruhend auf neuem Betonpiedestal

Additional to the steel plate bonding a horizontal steel truss is constructed between the 8 rafters and the front and back wall at a height of 10 m. This framework consists out of steel tie bars ø42 (Tensor-Detan system). These bars are connected to the rafters. A schematic view of the horizontal framework is shown in Figure 25. The framework after completion of the restoration is shown in Figure 26.

All these measures will reduce the possible deformations to a calculated maximum of 2 cm. This deformation will cause no damage to the wooden structure, or to the masonry walls. The ductile behaviour of the masonry brickwork and the lime mortar is able to take that amount of deformation without cracking of the masonry walls.

Restoration works of the abbey barn were completed in 2002.

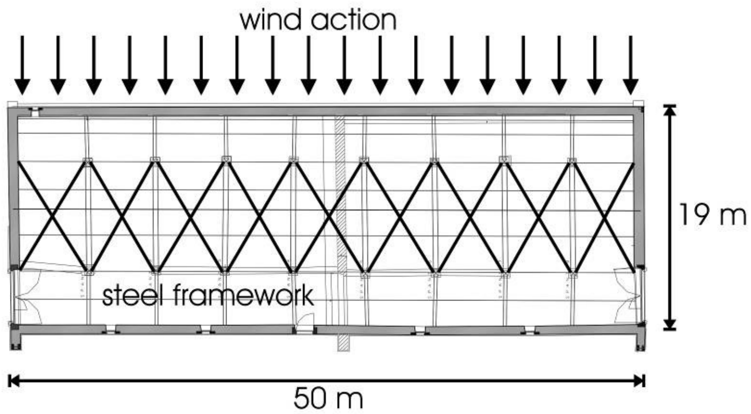

Figure 25 Steel framework to improve wind stability
Stahlfachwerk für Windstabilität

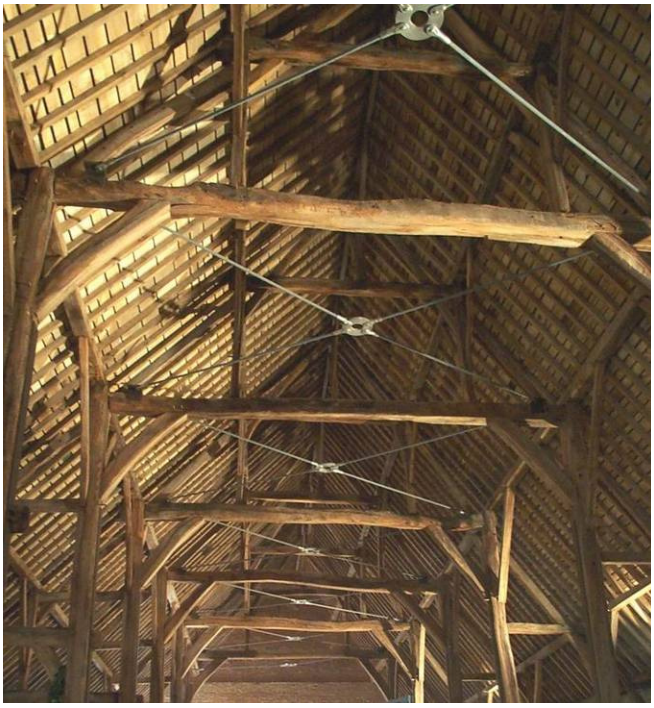
Figure 26 Framework after completion of restoration
Montiertes Stahlfachwerk

7. Conclusions

Merging of architectural, structural, material as well as societal aspects is needed in most restoration projects. The vision and appreciation of restoration options changes with time. It is the task of the design architect to guide the restoration process, not only in the technical sense, but even more important in the societal sense. The engineer supports the team with his knowledge on structures' and materials' behaviour, and always looks for innovative solutions to the benefit of the project, with full respect for the monument. If the architect manages to find the right compromise between the monument and society, giving the monument the appropriate new task, a successful restoration is within reach.

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